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Common waterhemp (*Amaranthus rudis* Sauer) management with soil-applied herbicides in soybean (*Glycine max* (L.) Merr.)

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Abstract

Amaranthus rudis can exhibit multiple emergence events during a crop growing season. Control of this species in soybean with soil-applied herbicides can be variable. A 2-yr field research project was conducted to examine the influence of herbicide application timing and dose on efficacy of six soil-applied herbicides for common waterhemp control in soybean. Four weeks after soybean planting, herbicides applied preemergence provided 18% greater common waterhemp control than when herbicides were applied 5 weeks early preplant. Herbicide dose did not significantly influence common waterhemp control, but differences among the six herbicides were evident. Sulfentrazone controlled common waterhemp better and reduced its density more than other herbicides. All herbicides reduced the weed density and dry weight more than the nontreated control.

Keywords: Weed control; Herbicide application timing; Herbicide application dose

1. Introduction

The genus *Amaranthus* comprises approximately 60 species, including both cultivated and weedy species. In the Great Plains region of the United States, approximately 10 *Amaranthus* species are considered troublesome in agronomic production systems. These include the monoecious species redroot pigweed (*A. retroflexus* L.), smooth pigweed (*A. hybridus* L.), Powell amaranth (*A. powellii* S. Wats.), tumble pigweed (*A. albus* L.), prostrate pigweed (*A. blitoides* S. Wats.), and spiny amaranth (*A. spinosus* L.), and the dioecious species common waterhemp (*Amaranthus rudis* Sauer), tall waterhemp (*A. tuberculatus* (Moq.) J.D. Sauer), Palmer amaranth (*A. palmeri* S. Wats.), and sandhills waterhemp (*A. arenicola* I.M. Johnst.) (Gleason and Cronquist, 1991; Horak et al., 1994). Accurate identification of these *Amaranthus* species during early vegetative development can be difficult as many exhibit similar morphological characteristics (Sauer, 1957; Ahrens et al., 1981; Wax, 1995) and because of the ability of several species to cross and produce hybrids with variable morphological characteristics (Murray, 1940; Sauer, 1957; Wetzel et al., 1999).

Until recently, the most common *Amaranthus* species in Midwest agronomic production systems was probably smooth pigweed (Wax, 1995), but currently other *Amaranthus* species are becoming more prevalent. In particular, infestations of the waterhemp species have become more frequent in Illinois agronomic production systems over the past 10 years. Many taxonomic references recognize common and tall waterhemp as discrete species, although discernable morphological characteristics are based on diminutive pistillate characteristics (Gleason and Cronquist, 1991; Horak et al., 1994). Wax (1995) suggests that common waterhemp is probably the dominant of the two species in the western portion of the Midwestern United States, while tall waterhemp occurs more frequently in the eastern portion. Examination of waterhemp collections from across a large portion of Illinois indicates common waterhemp is more prevalent than tall waterhemp. Some have proposed that in lieu of two discrete species, waterhemp exists as a single, polymorphic species (Pratt and Owen, 1999).

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Illinois soybean and corn (*Zea mays* L.) producers frequently have questioned why common waterhemp has recently become so predominant. Common waterhemp is an indigenous species of Illinois, historically common in natural ecosystems (Kenneth Robertson, personal communication). Examination of herbarium specimens from the Illinois Natural History Survey indicated common waterhemp collections were made in Illinois as early as 1948, decades prior to the rapid common waterhemp expansion during the early 1990s. Changes in agronomic production practices, differential susceptibility to herbicides, and development of herbicide-resistant biotypes have contributed to the increased incidences and severity of common waterhemp infestations (Hager et al., 1997; Sprague et al., 1997). Researchers in other regions of the Corn Belt and Great Plains have also reported similar increased prevalence of common waterhemp (Horak and Peterson, 1995; Hinz and Owen, 1997). Recent literature has reported incidences of herbicide resistance in common waterhemp populations, with emphasis on resistance to acetolactate synthase-inhibiting and triazine herbicides (Horak and Peterson, 1995; Anderson et al., 1996; Foes et al., 1998). Other contemporary research has examined the growth analysis of various *Amaranthus* species including common waterhemp (Horak and Loughin, 2000).

Research has demonstrated that germination and emergence of common waterhemp often extends further into the growing season, than is, common for other summer annual weed species (Steckel et al., 2001). Hartzler et al. (1999) determined the emergence characteristics of common waterhemp, giant foxtail (*Setaria faberi* Herrm.), woolly cupgrass (*Erichloa villosa* (Thunb.) Kunth), and velvetleaf (*Abutilon theophrasti* Medicus) in central Iowa. While the date of initial weed emergence varied among years, the emergence sequence among the four species was consistent across years. Woolly cupgrass and velvetleaf were the first species to emerge, while common waterhemp was consistently the last species to emerge, with initial emergence 5–25 days after velvetleaf. Additionally, common waterhemp had a longer emergence period than the other three species. Our observations from Illinois soybean and corn production fields support the findings of these authors. The extended emergence of common waterhemp can present significant management difficulties for soybean producers, especially in production systems such as no-till, that rely exclusively on herbicides for weed control. Soil-applied herbicides may not have sufficient soil residual activity to control late-emerging common waterhemp. Additionally, certain postemergence herbicides can control common waterhemp present at the time of application (Mayo et al., 1995), but generally do not control plants that emerge following application.

Previous research has examined the response of common waterhemp to several soil-applied herbicides in soybean, but few studies have examined the combined influence of herbicide application timing and rate on duration of common waterhemp control. Sweat et al. (1998) reported on the efficacy of several soil- and foliar-applied soybean herbicides on four *Amaranthus* species including two common waterhemp biotypes. In field experiments, all preemergence (PRE) herbicides evaluated 28 days after application provided good control of a common waterhemp biotype from Kansas, however, ALS-inhibiting herbicides provided poor control of an Iowa common waterhemp biotype. Krausz et al. (1998) examined common waterhemp control with various rates of sulfentrazone applied preplant incorporated alone and in combination with cloransulam. By 56 days after soybean planting, common waterhemp control was 96–100% with sulfentrazone alone and 86% or greater from any treatment combination containing sulfentrazone. Dirks et al. (2000) reported that sulfentrazone applied approximately 15 days prior to soybean planting at 0.22 kg ai/ha provided equivalent common waterhemp control 5 weeks after soybean planting as the application made at planting at two locations in 1998 and 1999. Few studies have reported on common waterhemp control when soil-applied herbicides are applied more than 15 days prior to soybean planting.

Many Illinois soybean fields are treated with a soil-applied herbicide either several weeks prior to planting or after planting but before crop emergence for common waterhemp control. Early preplant (EPP) herbicide applications have become popular in Illinois because of the benefit of spreading producer and custom applicator early season work load. Additionally, EPP applications in no-till production systems often increase the likelihood that adequate precipitation will be received prior to planting to move the herbicide into the soil solution. However, because the extended germination and emergence characteristics of common waterhemp (Hartzler et al., 1999; Steckel et al., 2001) frequently result in several emergence events, soil residual control might be extended further into the growing season if soil-applied herbicide applications are made closer to soybean planting. The objectives of this research were to: (1) evaluate six soil-applied herbicides, representing four modes of action, for control of common waterhemp in soybean, (2) determine if herbicide application timing influences the duration of common waterhemp control, and (3) determine if reduced doses of these soil-applied herbicides can provide an acceptable level of common waterhemp control.

2. Materials and methods

Field experiments were conducted during 1996 and 1997 at two locations each year. The University of

Illinois Brownstown Agronomy Research Center was a location both years, while the other location was a producer field located in Bond (1996) or Fayette (1997) County, Illinois. Soil information for each location is presented in Table 1. Soybean was planted in $3\,m \times 10\,m$ plots with a crop row spacing of 76 cm at each location. No primary or secondary tillage operation was performed prior to soybean planting at the producer field locations either year or at Brownstown in 1996. Existing vegetation at these locations was controlled prior to soybean planting with 840 g acid equivalent/ha glyphosate. Spring tillage with a field cultivator was performed prior to EPP herbicide application at Brownstown in 1997. Common waterhemp seed was spread at the Brownstown location both years 3–4 weeks prior to EPP herbicide application to supplement the natural population, whereas the indigenous common waterhemp population was sufficient at the producer field sites each year. Common waterhemp density averaged across all experimental locations in nontreated plots 4 weeks after soybean planting was 180 plants/m^2. This weed density averaged across all sites was sufficiently high to allow an excellent assessment of herbicide activity.

Selection of herbicides and application rates was based upon use practices among Illinois soybean producers and per label recommendations for soil texture and organic matter content. At the time this research was conducted sulfentrazone was not commercially available, therefore, sulfentrazone application rates were determined according to manufacturer recommendations. Herbicide treatments included dimethenamid at 1050 and 1310 g ai/ha, linuron at 560 and 840 g ai/ha, metolachlor at 1640 and 2740 g ai/ha, metribuzin at 260 and 420 g ai/ha, pendimethalin at 930 and 1390 g ai/ha, and suflentrazone at 280 and 420 g ai/ha. All herbicides were applied 5 weeks EPP and immediately following soybean planting (PRE) to determine the influence of herbicide application timing on the duration of common waterhemp control. Dates of all herbicide application timings and soybean planting are presented in Table 2. Soil temperature at a 10-cm depth was recorded at each herbicide application timing (Table 2). All herbicides were applied with no subsequent mechanical incorporation. A nontreated control was included for comparison at all locations. Herbicides were applied with a backpack CO_2 sprayer equipped with XR8003[1] flat fan spray tips 51 cm apart on a 3-m boom. Spray volume and pressure were 187 l/ha and 276 kPa, respectively.

Table 1
Soil characteristics for each experimental location in Illinois

Location	Year	Soil characteristics		
		Series	pH	Organic matter (%)
Brownstown	1996	Cisne silt loam (fine, smectitic, mesic, Vertic Albaqualfs)	6.7	1.5
	1997	Cisne silt loam (fine, smectitic, mesic, Vertic Albaqualfs)	6.6	1.4
Bond County	1996	Cowden silt loam (fine, smectitic, mesic, Mollic Albaqualfs)	6.8	2.1
Fayette County	1997	Bluford silt loam (fine, smectitic, mesic, Aeric Chromic Vertic Epiaqualfs)	6.8	2.1

Common waterhemp control was determined 5, 7, and 9 weeks after EPP application and 4, 6, and 8 weeks after PRE application using a scale ranging from 0% (no control) to 100% (complete control), based on visual determination of common waterhemp biomass reduction in the treated plot area compared with the nontreated control. Additionally, a 1 m^2 area between the middle two soybean rows of each plot was established during the initial visual evaluation, and common waterhemp plants were counted within this area at each evaluation timing. Following the final evaluation of PRE treatments, all common waterhemp plants within the 1 m^2 area of each plot were harvested, oven dried, and dry weights recorded.

A data set containing common waterhemp percent control and counts from the 9 weeks after EPP application evaluation and the 4 weeks after PRE application evaluation was created to determine the influence of herbicide application timing, selection, and rate 4 weeks after soybean planting. This date was selected as it corresponds to the approximate time when soybean producers determine if a postemergence herbicide application is necessary. By 4 weeks after soybean planting, EPP and PRE treatments had been in the soil environment for 63 and 28 days, respectively. Data from all other evaluation timings were analyzed separately.

2.1. Statistical analysis

The experimental design each year was a randomized complete block with 4 replications. All data were analyzed using the SAS MIXED procedure (SAS, 2000). All possible main effects and interactions were tested. Expected mean squares for appropriate tests of hypothesis were determined using the method described by McIntosh (1983). Each year–location combination was considered an environment as suggested by Carmer et al. (1989). Environments, replications (nested within environments), and all interactions containing either of

[1]XR8003 Teejet spray nozzles. Spraying Systems Co., North Avenue, Wheaton, IL 60189.

Table 2
Herbicide application and soybean planting dates for each experimental location in Illinois

Year	Location	Herbicide application timing				Soybean planting
		EPP[a]		PRE[b]		
		Date	Soil temperature (10 cm depth) (°C)	Date	Soil temperature (10 cm depth) (°C)	
1996	Bond County	April 17	7	May 23	17	May 23
	Brownstown	April 17	9	May 23	16	May 23
1997	Fayette County	April 17	7	May 14	18	May 14
	Brownstown	April 17	8	May 16	14	May 16

[a] EPP, early preplant.
[b] PRE, preemergence.

these effects were considered random effects; all other variables (herbicide, application rate, application timing) were considered fixed effects. Considering environments random effects broadens the possible inference space the experimental results are applicable to (Carmer et al., 1989). Individual treatment differences were determined using Fisher's protected LSD ($P = 0.05$). Nontransformed and arcsine of the square root transformed data of common waterhemp control were examined using the PROC UNIVARIATE procedure of SAS (SAS, 2000) to determine if data transformation improved the normality of the distribution. Transformation of the data did not improve the normality of the distribution, therefore, the analysis utilized the nontransformed data. A similar procedure was used to examine the nontransformed and log 10 transformed data of common waterhemp counts and biomass. Transformation of these data did not improve the normality of the distribution, therefore, the analysis was performed on the nontransformed data.

3. Results and discussion

Analysis of variance results of common waterhemp control 4 weeks after soybean planting indicated the main effects of application timing ($Pr > F = 0.0057$) and herbicide ($Pr > F = 0.0025$) were significant. The main effect of dose and all interactions of the three fixed effects were not significant ($Pr < 0.05$).

3.1. Influence of herbicide application timing on common waterhemp control

Common waterhemp control was greater when herbicides were applied PRE compared with EPP. When herbicides were applied PRE, common waterhemp control 4 weeks after soybean planting was 89% compared with 71% when herbicides applied were EPP (Table 3). The 18% difference in common waterhemp control between EPP and PRE application timing can have important implications for management of this species in soybean. The extended emergence characteristics of common waterhemp (Hartzler et al., 1999) frequently result in several emergence events during the growing season, and our results suggest timing of soil-applied herbicide application can influence the duration of residual control following crop emergence. Control of common waterhemp after soybean planting can be extended when soil-applied herbicides are applied at or close to planting rather than 5 weeks prior to planting. The extended residual control of common waterhemp attainable when soil-applied herbicides are applied PRE may allow subsequent postemergence soybean herbicide applications to be delayed until additional common waterhemp emergence has occurred. In contrast to these results, Dirks et al. (2000) reported no differences in common waterhemp control 5 weeks after soybean planting with sulfentrazone applied alone EPP or PRE, however, the EPP application timing in their research was only 15 days prior to soybean planting.

Table 3
Main effect of herbicide application timing on common waterhemp control 4 weeks after soybean planting, averaged across four environments

Application timing[a]	Common waterhemp control[b] (%)	$Pr > F$
EPP	71	0.0057
PRE	89	—

[a] EPP, early preplant; PRE, preemergence.
[b] Visual determination of common waterhemp biomass reduction compared with a nontreated control.

3.2. Influence of herbicide selection on common waterhemp control

All herbicides demonstrated activity on common waterhemp, but differences in the level of common waterhemp control among the herbicides were evident. Sulfentrazone provided 93% common waterhemp control 4 weeks after soybean planting which was greater than any other herbicide (Table 4). Other research also has indicated sulfentrazone is an effective soil-applied soybean herbicide option for common waterhemp control. Sulfentrazone applied alone at rates ranging from 170 to 350 g ai/ha has provided 100% (Sweat et al., 1998), 96–100% (Krausz et al., 1998), and 97–98% (Niekamp et al., 1999) common waterhemp control 4–7 weeks after planting.

Common waterhemp control with dimethenamid, linuron, metolachlor, metribuzin, and pendimethalin was 80% or less 4 weeks after soybean planting (Table 4). Metribuzin was less effective controlling common waterhemp than metolachlor, while dimethenamid, linuron, metolachlor, and pendimethalin provided a similar level of common waterhemp control. Sweat et al. (1998) also reported that metolachlor and dimethenamid provided equivalent common waterhemp control, but in contrast to our results, found pendimethalin less effective than metolachlor, and dimethenamid and metribuzin equally effective 28 days after application.

Analysis of variance results of common waterhemp density 4 weeks after soybean planting indicated the main effect of herbicide selection ($Pr > F = 0.0258$) was significant. The main effects of application timing and rate and all interactions of the three fixed effects were not significant.

Common waterhemp density in nontreated control plots averaged 180 plants/m^2 (Table 4). All herbicides reduced common waterhemp density compared with the nontreated control. Sulfentrazone reduced common waterhemp density to 4 plants/m^2, a 98% reduction compared with the nontreated control. No differences in common waterhemp density were found between dimethenamid, linuron, metolachlor, metribuzin, and pendimethalin. Overall, evaluation of herbicide efficacy determined by common waterhemp density produced results similar to those based on percent common waterhemp control 4 weeks after soybean planting.

Table 4
Main effect of herbicide on common waterhemp control and density 4 weeks after soybean planting, averaged across four environments

Herbicide	Common waterhemp control[a] (%)	Density (plants/m^2)
Sulfentrazone	93	4
Metolachlor	80	22
Pendimethalin	79	23
Dimethenamid	77	39
Linuron	77	28
Metribuzin	72	39
Nontreated	0	180
$LSD_{0.05}$	8	18

[a] Visual determination of common waterhemp biomass reduction compared with a nontreated control.

Common waterhemp control and density 5 and 7 weeks after EPP application and 6 and 8 weeks after PRE application are presented in Table 5. Common waterhemp control 5 weeks after EPP application was 91% or greater for all herbicides regardless of dose. Common waterhemp density ranged from 1 to 37 plants/m^2 but differences between herbicides or rates were not statistically different. By 7 weeks after EPP application common waterhemp control had declined to less than 90% for all treatments except sulfentrazone (both rates), metolachlor (2740 g ai/ha), and pendimethalin (930 g ai/ha) while common waterhemp density increased for all treatments.

Common waterhemp control 6 and 8 weeks after PRE application was greatest with sulfentrazone regardless of dose. No differences in common waterhemp control were apparent between herbicide rates except for dimethenamid and metribuzin, and metolachlor and dimethenamid 6 and 8 weeks after PRE, respectively. Common waterhemp density between 6 and 8 weeks after PRE application declined for all treatments except sulfentrazone and metolachlor (2740 g ai/ha). The decline in common waterhemp density was not attributable to herbicide activity since common waterhemp control values also declined during this time, but was likely attributable to intra- and interspecific species competition.

Common waterhemp dry weights of plants harvested from a 1 m^2 area following the final evaluation of PRE treatments are presented in Table 6. Analysis of variance indicated common waterhemp biomass was influenced by herbicide ($Pr > F = 0.0027$) but was not influenced by other fixed main effects or interactions.

All herbicides reduced common waterhemp dry weight at least 82% compared with the nontreated control. Similar to common waterhemp density, sulfentrazone reduced common waterhemp dry weight more than any other herbicide. No other differences between herbicides were significant.

The emergence characteristics of common waterhemp frequently result in several emergence events following soybean planting. Soil-applied herbicides can provide early season control, but a subsequent postemergence herbicide application may be necessary to obtain an acceptable level of common waterhemp control. While the herbicide application rates included in this research did not statistically influence common waterhemp control or density 4 weeks after soybean planting, growers should be aware that reducing herbicide application rates below label recommendations may sometimes result in reduced common waterhemp control. Sulfentrazone is an effective soil-applied herbicide option for common waterhemp control that provides good residual control following soybean planting. Timing herbicide application closer to crop planting may extend common waterhemp control further into the

Table 5
Common waterhemp control and density 5 and 7 weeks after EPP herbicide application and 6 and 8 weeks after PRE herbicide application, averaged across four environments

Herbicide	Rate (g ai/ha)	Weeks after EPP[a] application				Weeks after PRE[b] application			
		5		7		6		8	
		Control[c] (%)	Density (plants/m^2)	Control (%)	Density (plants/m^2)	Control (%)	Density (plants/m^2)	Control (%)	Density (plants/m^2)
Sulfentrazone	280	98	1	96	4	94	1	92	1
	420	99	1	97	4	97	1	94	1
Metolachlor	1640	94	17	85	29	70	44	50	35
	2740	97	4	91	14	74	26	59	26
Dimethenamid	1050	93	37	80	63	64	74	46	52
	1310	96	7	87	24	72	56	56	46
Pendimethalin	930	94	7	91	27	69	53	55	37
	1390	96	7	89	14	75	34	59	26
Linuron	560	91	33	80	53	66	38	51	27
	840	95	10	84	29	71	41	58	26
Metribuzin	260	92	20	82	36	52	76	43	30
	420	93	19	86	31	60	53	46	47
$LSD_{0.05}$	—	NS	NS	9	23	7	34	9	23

[a] EPP, early preplant.
[b] PRE, preemergence.
[c] Visual determination of common waterhemp biomass reduction compared with a nontreated control.

Table 6
Main effect of herbicide on common waterhemp dry weight from a 1 m^2 area following the 8 week evaluation of PRE treatments, averaged across four environments

Herbicide	Common waterhemp dry weight (g)
Sulfentrazone	5
Metolachlor	44
Pendimethalin	48
Dimethenamid	56
Linuron	35
Metribuzin	53
Nontreated	307
$LSD_{0.05}$	29

growing season compared with application 5 weeks EPP.

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References

Ahrens, W.H., Wax, L.M., Stoller, E.W., 1981. Identification of triazine-resistant *Amaranthus* spp. Weed Sci. 29, 345–348.

Anderson, D.D., Roeth, F.W., Martin, L.R., 1996. Occurrence and control of triazine-resistant common waterhemp (*Amaranthus rudis*) in field corn (*Zea mays*). Weed Technol. 10, 570–575.

Carmer, S.G., Nyquist, W.E., Walker, W.M., 1989. Least significant differences for combined analysis of experiments with two or three-factor treatment designs. Agron. J. 81, 665–672.

Dirks, J.T., Johnson, W.G., Smeda, R.J., Massey, R.E., 2000. Use of preplant sulfentrazone in no-till, narrow row glyphosate-resistant *Glycine max*. Weed Sci. 48, 628–639.

Foes, M.J., Liu, L., Tranel, P.J., Wax, L.M., Stoller, E.W., 1998. A biotype of common waterhemp (*Amaranthus rudis*) resistant to triazine and ALS herbicides. Weed Sci. 46, 514–520.

Gleason, H.A., Cronquist, A., 1991. Manual of Vascular Plants of the Northeastern United States and Adjacent Canada, 2nd Edition, New York Botanical Garden Press, New York.

Hager, A.G., Wax, L.M., Simmons, F.W., Stoller, E.W., 1997. Waterhemp management in agronomic crops. Univ. Illinois Bull. X855, 12.

Hartzler, R.G., Buhler, D.D., Stoltenberg, D.E., 1999. Emergence characteristics of four annual weed species. Weed Sci. 47, 578–584.

Hinz, J.R.R., Owen, M.D.K., 1997. Acetolactate synthase resistance in a common waterhemp (*Amaranthus rudis*) population. Weed Technol. 11, 13–18.

Horak, M.J., Loughin, T.M., 2000. Growth analysis of four *Amaranthus* species. Weed Sci. 48, 347–355.

Horak, M.J., Peterson, D.E., 1995. Biotypes of palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) are resistant to imazethapyr and thifensulfuron. Weed Technol. 9, 192–195.

Horak, M.J., Peterson, D.E., Chessman, D.J., Wax, L.M., 1994. Pigweed Identification: A Pictorial Guide to the Common Pigweeds of the Great Plains. Kansas State University, Manhattan, KS, p. 12.

Krausz, R.F., Kapusta, G., Matthews, J.L., 1998. Sulfentrazone for weed control in soybean (*Glycine max*). Weed Technol. 12, 684–689.

Mayo, C.M., Horak, M.J., Peterson, D.E., Boyer, J.E., 1995. Differential control of four *Amaranthus* species by six postemergence herbicides in soybean (*Glycine max*). Weed Technol. 9, 141–147.

McIntosh, M.S., 1983. Analysis of combined experiments. Agron. J. 75, 153–155.
Murray, M.J., 1940. The genetics and sex determination in the family Amaranthaceae. Genetics 25, 409–431.
Niekamp, J.W., Johnson, W.G., Smeda, R.J., 1999. Broadleaf weed control with sulfentrazone and flumioxazin in no-tillage soybean (*Glycine max*). Weed Technol. 13, 233–238.
Pratt, D.B., Owen, M.D.K., 1999. Species circumscriptions of common and tall waterhemp. Proc. North Cent. Weed Sci. Soc. 54, 171.
SAS Institute, 2000. SAS User's Guide Version 8. SAS Institute, Cary, NC.
Sauer, J., 1957. Recent migration and evolution of the dioecious Amaranths. Evolution 11, 11–31.
Sprague, C.L., Stoller, E.W., Wax, L.M., 1997. Response of an acetolactate synthase (ALS)-resistant biotype of *Amaranthus rudis* to selected ALS-inhibiting and alternative herbicides. Weed Res. 37, 93–101.
Steckel, L.E., Sprague, C.L., Simmons, F.W., Bollero, G., Hager, A., Stoller, E.W., Wax, L.M., 2001. Tillage and cropping effects on common waterhemp (*Amaranthus rudis*) emergence and seed bank distribution over four years. Weed Sci. Soc. Am. Abstr. 41, 321.
Sweat, J.K., Horak, M.J., Peterson, D.E., Lloyd, R.W., Boyer, J.E., 1998. Herbicide efficacy on four *Amaranthus* species in soybean (*Glycine max*). Weed Technol. 12, 315–321.
Wax, L.M., 1995. Pigweeds of the midwest - distribution, importance, and management. Proc. Iowa Integrated Crop Manag. Conf. 7, 239–242.
Wetzel, D.K., Horak, M.J., Skinner, D.Z., Kulakow, P.A., 1999. Transferal of herbicide resistance traits from *Amaranthus palmeri* to *Amaranthus rudis*. Weed Sci. 47, 538–543.